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A Methodology for Obtaining Voltage and Current Ripples of Power Electronics Converters with a Fixed Node on their Output

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Abstract

This paper presents a methodology for obtaining voltage and current ripples for power electronics (PE) converters which have a fixed node on its output. The operation principle of PE converters basically consists of closing and opening a power switch for regulating the voltages and currents of the system according to their control objectives. In this paper, the analysis is performed with PE converters with a node in the output which topology does not change for both switching states; in other words, the differential equations that govern the behavior of output current do not depend on the duty cycle. According to the literature review, most researches focus on modelling and controlling PE converters; however, to the best of the authors' knowledge, a detailed methodology for deducing ripples of PE converters has not yet been reported. Ripples are necessary for appropriately sizing the passive elements in the design stage. The methodology is explained using the Buck converter; nonetheless, it can be applied for any PE converter that has a fixed node on it output. Finally, OpenModelica software is used for validating the proposed methodology.

Keywords: Voltage and current ripples, Power Electronics (PE) devices, Differential Equations (DE), OpenModelica.

I. INTRODUCTION

Deduction of voltage and current ripples are useful in the design stage of a converter for correctly sizing passive elements, basically inductors (L) and capacitors (C). Engineers, in the design stage, must comply with ripple requirements that loads or applications may have. Voltage and current ripples depend on: values of inductor and capacitors, switching frequency, duty cycle and output voltage. Usually, current ripples equations are easy to determine; however, the deduction of output voltage ripples equations has a greater degree of difficulty for two reasons: 1) output capacitor stores and delivers energy during the same switching state, for both closed and open switching states. 2) Voltage ripple depends on current ripple. This paper presents a methodology for obtaining voltage and current ripples in converters that have a fixed node on their output.

Using the geometric representation of voltage and current ripples, this paper develops a rigorous explanation for deducing the mathematical expression that governs the behavior of ripples in converters. The explanation is presented for giving specific details that can be useful for electrical, control and electronical engineers. The contributions of most power electronic design papers are related to the use of the model, failing to present details regarding the deduction of aspects such as voltage and current ripples. However, such details are of paramount importance, especially for PE designers, since references allow stablishing the design requirements in the designing stage [1]-[8].

The dynamical performance can be understood if the operation principle and ripples are explained in detail, which may lead to better setting the requirements established from the design stage [9]. There are a lot of papers that partially include the explanation of the obtention of voltage and current ripples; nonetheless, there are still many gaps in the knowledge [10]-[12]. The main contribution of this paper lies on the deduction of voltage and current ripples that permits a deeper explanation of the operation principle for PE devices. The proposed methodology can be easily applied to other type of converters [13]-[14]. After the deduction of voltage and current ripples, the proposed procedure is validated using the OpenMoedlica software.

OpenModelica [15] is open source software designed for the simulation of PE devices, allowing dynamic multi-domain simulation of linear and non-linear systems. OpenModelica is made of an equation-based and object-oriented language known as *Modelica*. OpenModelica features extensive model libraries in several fields, as well as other resources such as a graphic connection editor (OMEdit), a compiler, a simulator and plotting tools. OpenModelica is widely used in industrial and research applications on electric and electronic engineering. The authors in [16] used the *Modelica* language in studies of DC microgrids. In [17] the authors simulated electrical power networks, proposing a Power System Library; also, in [18] control algorithms are implemented using OpenModelica for power inverter applications. The aforementioned studies evidence that OpenModelica is a tool for improving the formation of future engineers [19]. In this paper, OpenModelica is used as a validation tool for verifying the obtained reference voltages and currents.

This paper is organized as follows: Section II presents the proposed methodology using the Buck converter. Section III corresponds to the results obtained in OpenModelica for validating the proposed methodology. Section IV concludes and highlights the most relevant aspect of this paper.

II. PROPOSED METHODOLOGY

The proposed methodology is explained using the Buck converter depicted in Figure 1. v_i is the input voltage; L is an inductors; C is a capacitor; Q is a power switch, D is a power diode; and R is the resistors used as a load. The following assumptions have been made: 1) Losses are neglected. 2) voltage drop in power switches is not considered. 3) The passive law of sign is used to obtain voltage and current references of the system that are drawn with red color.

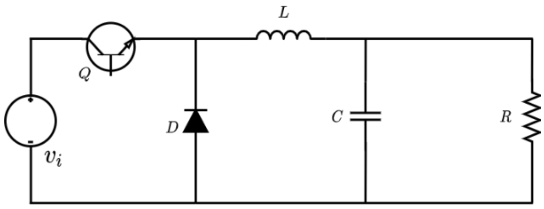
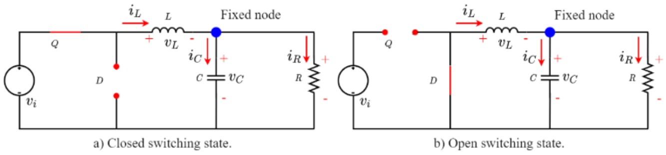


Figure 1. Buck converter topology

Figure 2 shows the converter for both switching states. Figure 2(a) corresponds to Q closed while Figure 2(b) corresponds to Q open. Note that for both switching states, the node on the output does not change its topology (fixed node).



a) Closed switching state. b) Open switching state.

Figure 2. Switching states of the buck converter

Equations (1) and (2) were obtained after applying Kirchhoff laws in Figure 2(a) while Equations (3) and (4) were obtained after applying Kirchhoff laws in Figure 2(b).

$$L\frac{di_L}{dt} = v_i - v_C \tag{1}$$

$$C\frac{di_C}{dt} = i_L - i_R = i_L - \frac{v_c}{R} \tag{2}$$

$$L\frac{di_L}{dt} = -v_C \tag{3}$$

$$C\frac{di_C}{dt} = i_L - i_R = i_L - \frac{v_c}{R} \tag{4}$$

Please note that Equation (2) and (4) are the same. This is due to the fixed node on the output. Figure 3 correspond to the voltage and current waveforms of the converter. Figure 3(a) is the Pulse Width Modulation (PWM) signal for controlling the converter. Q is closed between 0 and DT_{sw} while is open in the complementary period ($(1-D)T_{sw}$) between DT_{sw} and T_{sw}. Figure 3(b) is the waveform of i_L, being I_L its mean value and Δi_L its ripple. Figure 3(c) is the current waveform of the load which is assumed constant. Figure 3(d) is the capacitor current (i_C) and Δi_C is its respective ripple, for a correct operation of the converter its mean value must be zero ($I_C = 0$). Figure 3(e) is the capacitor voltage waveform (v_C), Δv_C is its ripple and V_C is its mean value.

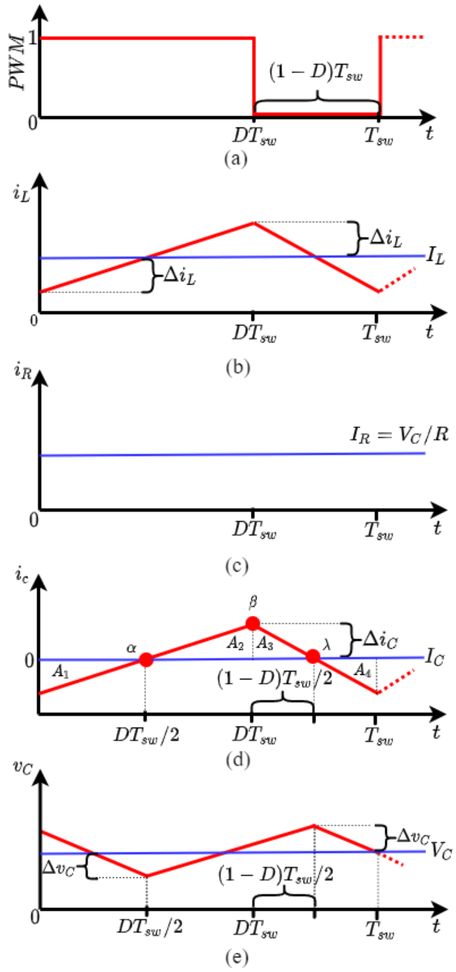


Figure 3. Voltages, current, and ripples representation.

The current ripple (Δi_L) can be obtained from Equations (1) and (3); however, Equation (3) is simpler. Then, Equation (3) is discretized ($L\frac{\Delta i_L}{\Delta t} = -V_C$) with $\Delta t = (1-D)T_{sw}$ where D is the duty cycle and T_{sw} is the switching period. The current ripple must be divided by 2 since ripples are usually obtained with respect to the mean value of the signal. Equation (5) indicates the current ripple, where V_C and I_L are the mean values of v_C and i_L, respectively; while f_{sw} is the switching frequency.

$$\Delta i_L = \frac{V_C(1-D)T_{sw}}{2L} = \frac{V_C(1-D)}{2Lf_{sw}} \tag{5}$$

The correct operation of the converter stablishes that the mean value of I_C must be zero. In consequence, areas A_1 and A_2 in Figure 3(d) must be equal; A_3 and A_4 are also equal. Please note, that zero crossing when Q is closed is in the time instant of $(DT_{sw}/2)$ (α point) while zero crossing when Q is open is in the time instant of $(DT_{sw} + (1-D)T_{sw}/2)$ (λ point). The deduction of the voltage ripple in the capacitor (Δv_C) considers the following assumptions: 1) the load current (I_R) is constant. 2) the inductor current ripple is equal to the capacitor current ripple ($\Delta i_L = \Delta i_C$). 3) voltages and currents increase and decrease linearly. Δv_C can be deduced using the triangle $\alpha\beta\lambda$ ($A_{\alpha\beta\lambda}$) of Figure 3(d):

$$\int i_C dt = A_2 + A_3 = A_{\alpha\beta\lambda} = \frac{1}{2} \cdot base \cdot height \qquad (6)$$
$$= \frac{1}{2} \cdot base \cdot height$$

Where $base$ and $height$ are respectively the base and the height of triangle $A_{\alpha\beta\lambda}$. The base of the triangle (segment $\alpha\lambda$) is ($\lambda - \alpha = [DT_{sw} + (1-D)T_{sw}/2$)]-[$DT_{sw}/2$]= $T_{sw}/2$ while its height is Δi_C.

$$\int C \frac{dv_c}{dt} dt = \int_{V_C-\Delta v_C}^{V_C+\Delta v_C} dv_c = \frac{\Delta i_C}{4 f_{sw}} \qquad (7)$$

Replacing (5) in (7) the expression given in Equation (8) it is obtained:

$$\Delta v_C = \frac{V_C(1-D)}{16 f_{sw}^2 LC} \qquad (8)$$

IV. RESULTS

A simulation was carried out using the default compiler and solver in OpenModelica connection editor (OMEdit), version 3.2.2. Figure 4 show the implementation in OpenModelica of the converter depicted in Figure 1. The duty cycle used is 50% while the switching frequency is 1 kHz. The Buck converter was parametrized as follows: $L = 10\ mH$, $C = 1000\ \mu F$, $R = 10\ \Omega$, $v_i = 100$ V.

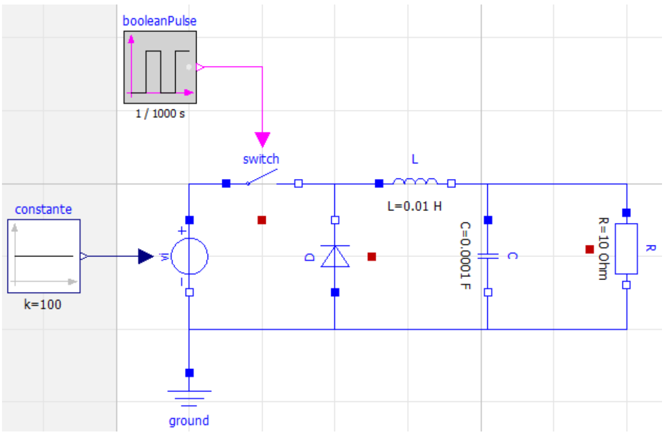


Figure 4. Implementation in OpenModelica.

Figures 5 and 6 show the voltage and current waveforms, respectively, with their respective ripples obtained with the simulation. Note that the theoretical calculation and simulation match, which validates the proposed methodology.

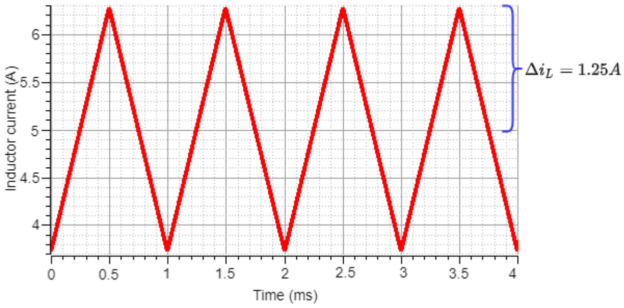


Figure 5. Current waveform and its ripple.

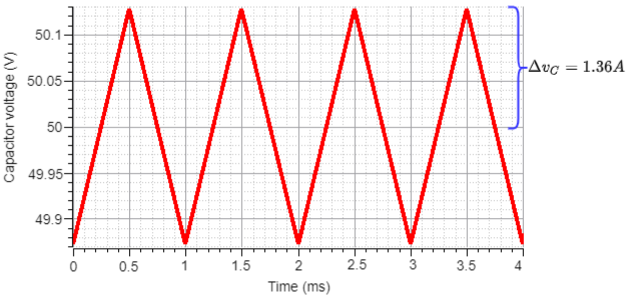


Figure 6. Voltage waveform and its ripple.

V. CONCLUSIONS

This paper presented a methodology for obtaining voltage and current ripples in PE converters. The methodology focused on converters that have a fixed node on their output. The proposed methodology explains in detail the mathematical procedure; basically, there was used a geometric representation of the ripples for deducing the ripples. It is concluded that voltage ripple depends on current ripple and the way that ripples are related is the contribution of this paper. It is highlighted that voltage ripple is inversely proportional to the square of the switching frequency, so this kind of converters tend to have small voltage ripples. The methodology was validated through the implementation of the converter in OpenModelica software; it is concluded that the proposed methodology correctly determines the voltage and current ripples for PE converters.

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